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Fault Detection and Diagnosis in Nonlinear Systems

A Differential and Algebraic Viewpoint

Springer

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To my wife and sons
Marilen, Rafael and Juan Carlos.

To my parents and brothers
Carlos, Virginia, Victor, Arturo,
Carlos, Javier and Marisela.

Rafael Martínez-Guerra

To my students

Juan Luis Mata-Machuca

Preface

This book is about faults aspects of detection and diagnosis problems in nonlinear systems which are represented by ordinary differential equations from a differential and algebraic viewpoint. This framework so important for fault detection and diagnosis, is not commonly found in text books. A prominent role is played by the type of mathematical tool used which is the main ingredient to the solution of some real problems. The background material needed to understand this book is differential algebra and differential equations. This book can be used by students with a strong first year of algebra and differential equations, it is oriented mainly toward upper division engineering and science students. It can also be used for a graduate course. We have rather tried to unify the theory as much as possible with the practice by focussing attention on a greatest number of techniques or procedures to tackle the general problem. Our goal in this book is to develop techniques using auxiliary systems named also “observers” to solve the fault detection and diagnosis problem in nonlinear systems. The level of rigor is high, and almost everything is proved. We have tried to develop proofs that add insight to the theorems and that are important methods. We have avoided the introduction of some concepts in order to make the book more widely readable, but the main ideas can easily be seen in this book.

The plan of the book is as follows:

In first two chapters, specially chapters 1 and 2, give a rather intensive and complete study of the fault detection problem using residual generators by considering two types of faults with application to an electromechanical positioning system and a Continuous Stirred Tank Reactor (CSTR). Chapters 3 and 4 are devoted to fault diagnosis problem. We introduce some concepts such as the “differential transcendence degree” to attack this problem, as well as we introduce the concept of “diagnosability condition” based on algebricity of the fault and we establish some strong results on the minimal number of measurements which are proved using the differential transcendence degree with application to a bioreactor model and a hydraulic system. In chapter 5 is studied a fault detection method to detect the belt breakdown in an experimental belt drive system using a proportional reduced order observer. In chapter 6 is dealt the fault diagnosis problem using the left invertibility condition, trough the concept of differential output rank, the methodology is tested in an experimental implementation of a three-tank system. In chapter 7 is boarded de fault estimation problem using a sliding mode observer and the so called Linear time-varying (LTV) differentiators. In chapter 8 is tackled the diagnosis problem for non-differentially flat and Liouvillian systems by using the concepts of differential transcendence degree and Hardy differential field. Finally, chapter 9 is devoted to the diagnosis problem using a polynomial observer to be tested in the experimental setting Amira DTS200 (three-tank system).

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Notations and symbols

$\approx$	approximately equal
$:=$	defined as
$<$ ($>$)	less (greater) than
$\leq$ ($\geq$)	less (greater) than or equal to
$\forall$	for all
$\in$	belongs to
$\subset$	subset of
$\cup$	union of sets
$\{\cdot\}$	set
$\to$	tends to
$\Rightarrow$	implies
$\Longleftrightarrow$	equivalent to, if and only if
Σ	summation
$\mathbb{R}$	the set of real numbers
$\mathbb{R}^+$	positive real numbers
$\mathbb{R}^{m\times n}$	the set of all $m \times n$ matrices with elements from $\mathbb{R}$
$\mathbb{R}_+^{m\times n}$	the set of all $m \times n$ matrices with elements form $\mathbb{R}^+$
$\det A$	the determinant of a square matrix $A \in \mathbb{R}^{n\times n}$
A^T	the transpose of a matrix obtained by interchanging the rows and columns of A
$\operatorname{rank} A$	the minimal number of linearly independent rows or columns of $A \in \mathbb{R}^{m\times n}$
A^{-1}	inverse of A
max	maximum
min	minimum
sup	supremum, the least upper bound
inf	infimum, the greatest lower bound
B_R	the ball $\{x \in \mathbb{R}^n \mid \|x\| \leq R\}$
$f : S_1 \to S_2$	a function f mapping a set S_1 into a set S_2
$\lambda_{\max}(P)$ ($\lambda_{\min}(P)$)	the maximum (minimum) eigenvalue of a symmetric matrix P
$P > 0$	a positive definite matrix P
$\operatorname{sign}(\cdot)$	the signum function
$f' = \frac{df}{dt}$	the first time derivative of f

$\dot{y}$ the first derivative of y with respect to time
$\ddot{y}$ the second derivative of y with respect to time
$\dddot{y}$ the third derivative of y with respect to time
$y^{(i)}$ the ith derivative of y with respect to time
lim limit
$|a|$ absolute value of a scalar a
$\|x\|$ the Euclidean norm of a vector
difftrd° differential transcendence degree
∞ infinity
$\square$ designation of the end of proofs